

3D-INTEGRATED MULTI-SENSOR DEMONSTRATOR SYSTEM FOR ENVIRONMENTAL MONITORING

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ABSTRACT

This paper summarizes the outcome of the EC FP7 project MSP - Multi Sensor Platform for Smart Building Management (Grant Agreement No. 611887). The MSP consortium comprising 17 partners from 6 European countries developed a full manufacturing chain for 3D system integration, which has never been realized before. It enables 3D-integration of highly sophisticated components and sensor devices on a CMOS electronic platform chip. The final multi-sensor system comprises a variety of gas sensors as well as optical sensors for ultraviolet, visible and infrared light. The MSP demonstrator system implemented in a wearable wristband device integrates a total of 57 sensors – this is a worldwide unique sensor system.

KEYWORDS

Smart Sensor System, Multi-Sensor Device, 3D-System Integration, Heterogeneous Integration, Multifunctional Nanomaterials.

INTRODUCTION

Indoor air quality monitoring is a big issue for health and well-being. The most sophisticated approach is using CO₂ and humidity monitoring to adapt ventilation in

rooms. Several sensor systems are on the market: SAMSUNG SmartThings [1], the AEOTEC MultiSensor 6 [2], or the Kentix - Multisensor DOOR [3], which consist of different devices such as motion, vibration, humidity, or temperature sensors for household applications. Waspmote [4] is a multi-sensor module to detect the presence of different gases, which is done by commercial gas sensors. Another approach is the Bosch BME680 [5] offering humidity, temperature, pressure, and VOC measurement. All those system employ a modular approach, are not integrated in CMOS technology, and do not provide wireless connectivity.

In this paper we present a multi-sensor system dedicated for indoor environmental monitoring in smart buildings comprising a total of 57 sensors: 52 gas sensors, a UV-A/B sensor, a visible light sensor, a temperature sensor, an infrared sensor, and a humidity sensor. All sensor devices have been 3D-integrated on a 20 x 20 mm² CMOS platform chip, which includes the required electric circuitry.

DEVELOPMENT OF COMPONENTS AND SENSOR DEVICES

Major objective was the development of a powerful manufacturing chain enabling 3D-integration of a variety

of components and sensor devices on a common CMOS platform chip. As shown in Fig.1. the initial approach was that all components and devices as well as the platform chip are suitable for Through-Silicon-Via (TSV) technology. This approach should enable a straightforward 3D-stacking with minimum footprint and without requiring any wire bonding.

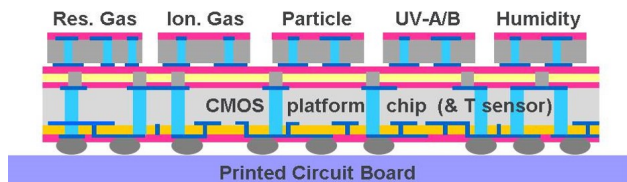


Figure 1: Schematic view of 3D-integrated sensor devices on a CMOS platform chip.

Following this approach a huge variety of components and devices have been developed within the MSP project:

- CMOS integrated gas sensors based on micro-hotplates (μ hps) and nanomaterials such as SnO_2 , CuO , ZnO and WO_3 nanowires (NWs), (bi)metallic nanoparticles (NPs), and their hybrid combinations,
- Humidity sensor based on graphene(oxide),
- An electronic platform chip based on TSV technology as stacking platform for the sensor devices,
- Development of GaN-on-Si technology based μ hp and integration of GaN/AlGaIn 2-D electron gas sensor for NO_2 ,
- Realization of hybrid MEMS-FBAR based micro sensor system utilizing high frequency acoustic wave devices for the real time monitoring of airborne fine particulates,
- SiC-based UV-A/B sensors, development of sensors for visible light with near photopic responsivity, and development of thermopile-based infrared sensors,
- Development of optimized photovoltaic energy harvester based on black-Si and interdigitated back contact with double side passivation using Al_2O_3 ,
- Development of piezoelectric energy harvester based on transparent, flexible and thin PVDF films (P(VDF-TrFE) and P(VDF-TrFE-CTFE)),
- Development of microcontroller SoC with record computing efficiency being a $10\times$ improvement compared to the 2017 research state of the art.

Lot of progress was achieved in the development of all components and devices. For example, gas sensors ranging from highly sophisticated devices based on nanowires, nanoparticles, and graphene to a commercially available sensor were developed. This has been achieved by implementing specific post-processing technologies enabling heterogeneous integration of basically CMOS incompatible materials (metal oxides, graphene, nanowires,...) on CMOS devices. Specific emphasis was on CO_2 sensing, which is of essential importance for smart building and smart home applications. The development and fabrication of the platform chip based

on TSV technology as carrier for the sensor devices was successfully achieved. A miniaturized wireless communication module for the MSP demonstrator device based on the 40 nm radio chip technology that achieves reduced supply voltage, power consumption, and chip area including an ultra-low-power microcontroller was developed.

Extensive characterization and measurements of all components and devices have been performed in specific test labs to select the devices suitable for final 3D-integration on the platform chip. An important criteria for final selection were the technology readiness levels (TRLs) of the components and devices. Due to their comparatively low TRL and 3D integration issues the photovoltaic and piezoelectric energy harvesters and the particle sensor were not selected for integration on the final demonstrator. Also the devices for wireless communication were not implemented on the platform chip but on the final PCB.

MANUFACTURING CHAIN FOR 3D INTEGRATION

A unique highly complex full manufacturing process flow has been realized to enable the fabrication of the 3D-stacked multi-sensor system. Due to the diversity of the technologies and materials, some devices, such as the SiC-based UV-sensor or the GaN-based NO_2 -sensor were not suitable for TSV technology and required wire bonding. Thus a combined approach based on TSV-technology and wire bonding has been performed.

A specific process based on the film-assisted molding technology has been applied to realize the fully overmolded MSP demonstrator system exhibiting an extremely challenging topography due to different thicknesses and geometries of the devices. Such a complex sensor system including fragile structures such as μ hp-structures and NWs has never been overmolded before. Fig.2 shows the complex tool, which has been fabricated and employed for the overmolding process.



Figure 2: Tool employed for overmolding the MSP-demonstrator system.

MULTI-SENSOR SYSTEM DEMONSTRATOR

The MSP demonstrator is a fully 3D-integrated overmolded multi-sensor system with a size of $20 \times 20 \text{ mm}^2$ comprising a total of 57 sensor – this is a unique

sensor system worldwide (Fig.3). A description of the devices and their functionality is presented in Fig.4. The following devices have been 3D-integrated on the platform chip:

- 3 CMOS chips, each of them containing an array of 8 μ hps, each one for 2 gas sensor with a total of $3 \times 8 \times 2 = 48$ devices for CO, CO₂, and VOC detection,
- 1 gas sensor for NO₂ employing GaN/AlGaN 2-D electron gas detection based on a GaN-on-Si μ hp,
- 1 humidity sensor based on graphene oxide,
- 1 calibrated temperature sensor,
- 1 SiC-based UV-A/B sensor,
- 1 visible light sensor with near photopic responsivity
- 1 infrared light sensor based on Si thermopiles,
- 2 gas sensors integrated on SiN μ hps for CO and VOCs,
- 1 gas sensor employing SnO₂ NWs for O₃ detection.

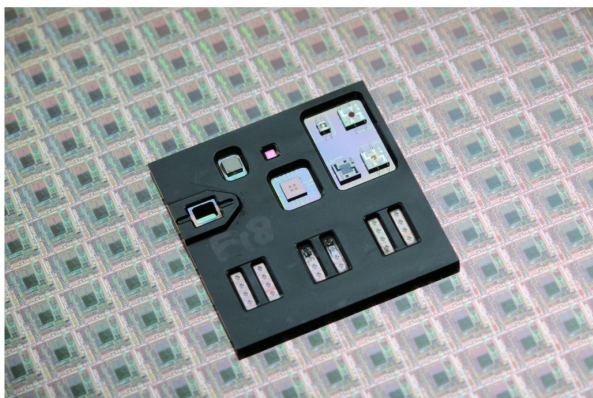


Figure 3: Overmolded MSP-demonstrator system comprising 57 sensor devices.

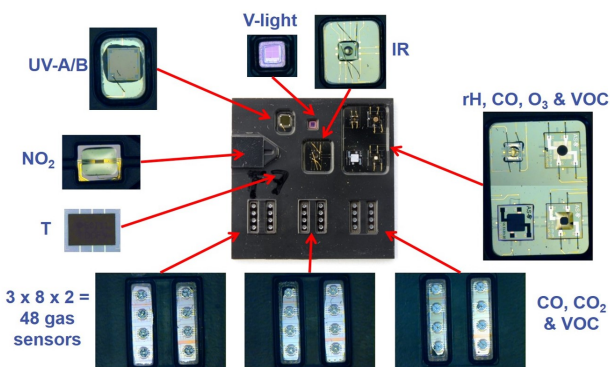


Figure 4: Schematic view of 3D-integrated sensor devices on a CMOS platform chip, and their functionality.

The MSP-demonstrator system was mounted on a specific PCB which includes the wireless communication (Fig.5). Finally a wearable wristband device was designed and fabricated as housing for the MSP demonstrator device.

The wearable wristband device with integrated MSP-demonstrator being the ultimate output of the MSP-project is shown in Fig.6. This is by far the most challenging wearable demonstrator system ever realized

with respect to minimum footprint, minimum power consumption, and maximum number of sensor devices.

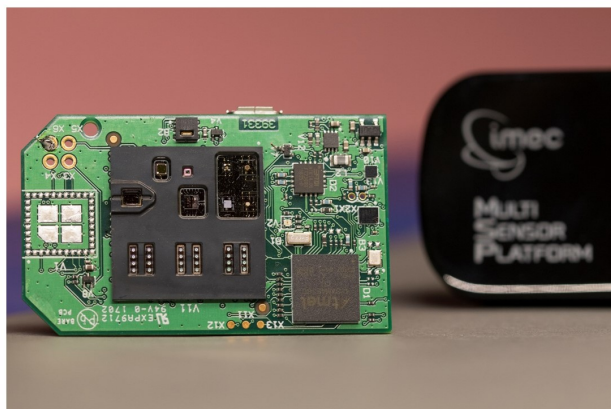


Figure 5: Final MSP-demonstrator system mounted on a specific PCB including wireless communication.



Figure 6: The ultimate output of the MSP-project - a wearable wristband device with integrated multi-sensor system.

NANOMATERIALS FOR CHEMICAL SENSORS

Chemical sensors based on CMOS integrated μ hps are one of the core developments of the MSP project. A new device comprising an array of 8 μ hps each one for 2 gas sensors resulting in a total of 16 chemical sensors on a single chip has been designed and fabricated. The μ hps are based on poly-Si-heaters and integrated thermocouples for μ hp temperature control. This chip includes an additional temperature reference for thermocouple calibration. The multi-sensor device is a worldwide unique gas sensor array and is shown in Fig.7.

The geometry of a single μ hp comprising two SnO₂ thin film sensors is presented in Fig.8. The electrodes for contacting the gas sensitive films are fabricated on the front side of the device. The μ hp has been fully released by employing an isotropic etching process, which provides excellent thermal insulation.

Different nanomaterials have been employed for realization of the gas sensor devices:

- Ultrathin (50 nm) gas sensitive SnO₂ films have been deposited on the μ hps by spray pyrolysis for CO and VOC detection,
- CuO-NWs have been synthesized on the μ hps by

thermal oxidation of Cu-films for CO₂ detection.

Both types of sensor devices have been functionalized with (bi)metallic NPs such as Au, NiPt, AuPd, AuPt, Pt, as well as ZrO₂ in order to improve the sensitivity and selectivity of the sensor devices. Fig.9 shows the response of a CuO-NW sensor functionalized with hybrid NPs to CO₂. The response of the sensor to CO₂ is almost independent of the humidity level [7].

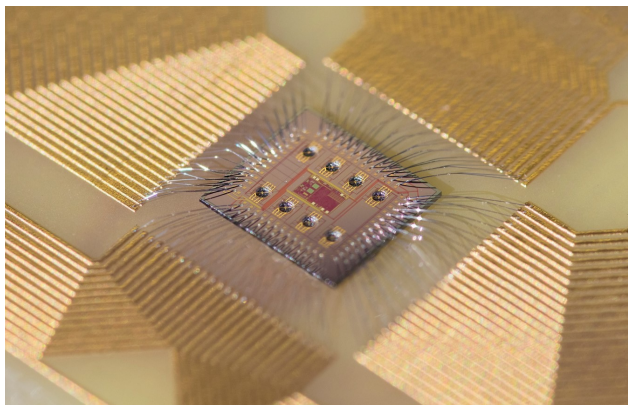


Figure 7: New 8 x array μ hp chip comprising 16 gas sensors bonded on chip carrier for performance characterization.

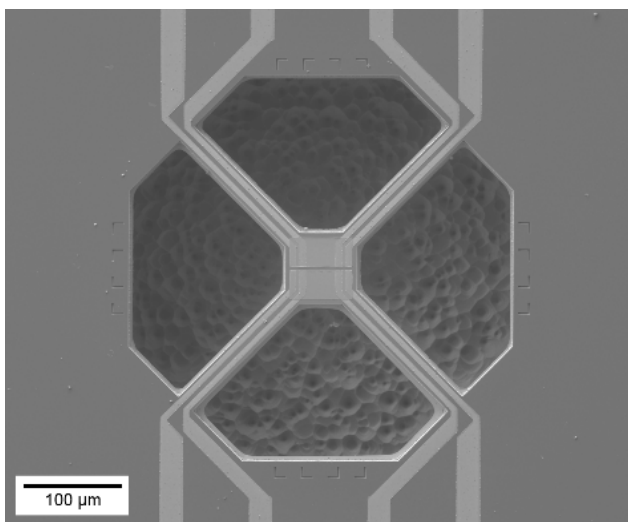


Figure 8: μ hp comprising a set of two single gas sensors.

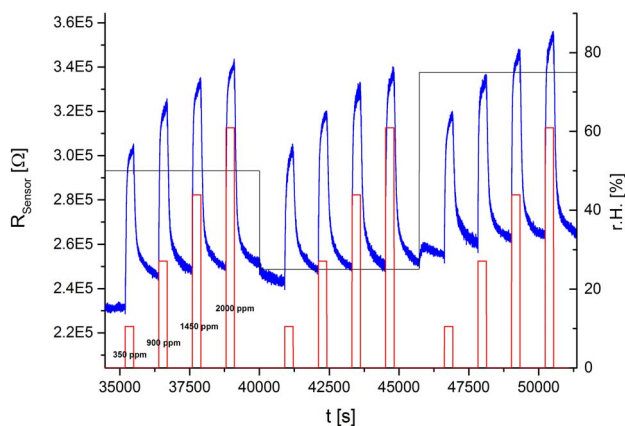


Figure 9: The response of CuO-NWs/hybrid-NPs sensor to CO₂ is independent of the humidity level.

SUMMARY AND OUTLOOK

Realization of the highly challenging full manufacturing chain for 3D smart system integration including overmolding is the most important innovation of the MSP project. The impact of the MSP innovation results from the outstanding variety of technologies, processes, nanomaterials, devices and 3D-integrated system, which have been realized.

The MSP-project addresses both environmental as well as societal needs: The MSP devices can be employed in smart phones for individual environmental monitoring indoors and outdoors as well as for breath analysis being an emerging technology for early screening of health issues. The MSP device can be employed for efficient control of Heating, Ventilation and Air-Conditioning in buildings to save energy, to reduce costs, and thus to reduce CO₂ emission without compromising the comfort.

The MSP device can find and measure pollutants harming our health and changing the climate as well as sense light or measure temperature and humidity. Armed with this information, wristband wearers might seek cleaner air by taking a certain street or opening the window to an airless or smoky room. Equipped with such a tool, wearers are empowered to assess their own environment indoors and outdoors and take actions to improve it when needed.

Demonstrating the ultimate state-of-the-art in multi-sensor system integration worldwide, the MSP project paves the way for future integrated smart sensor systems.

ACKNOWLEDGEMENTS

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